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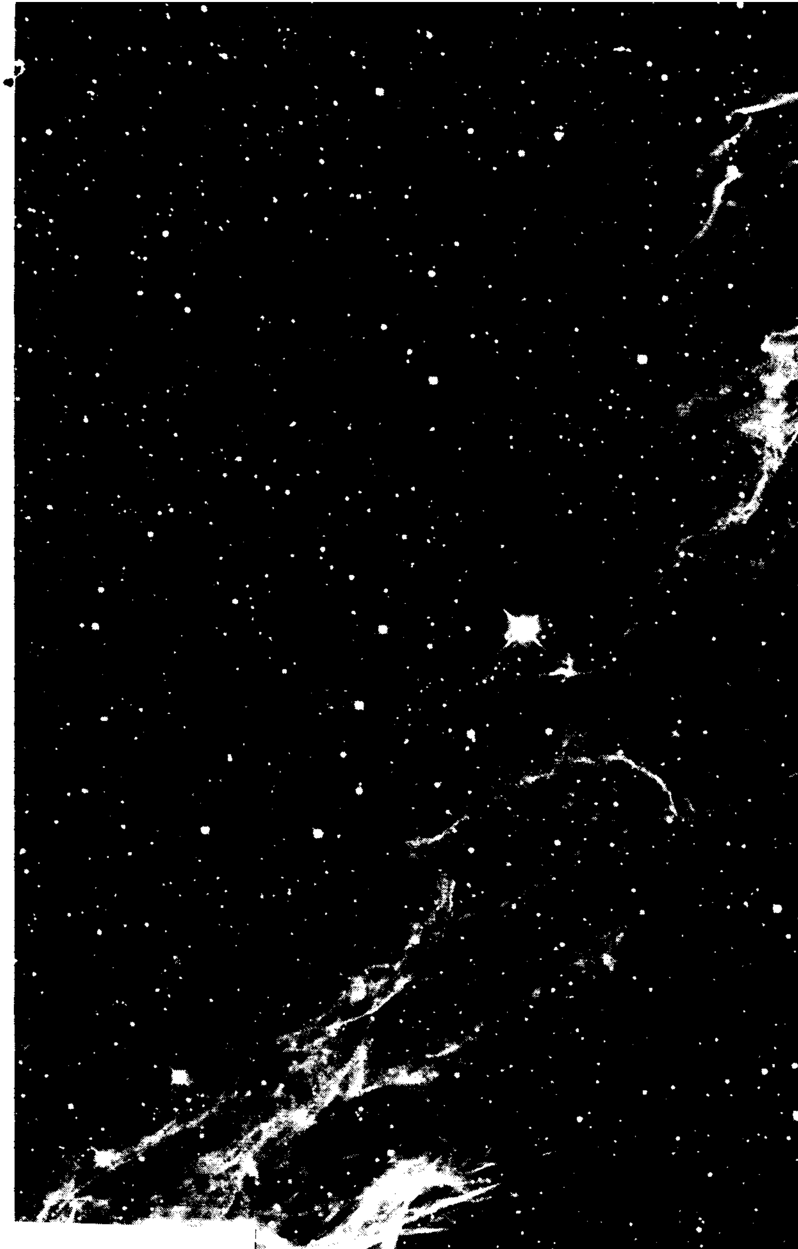

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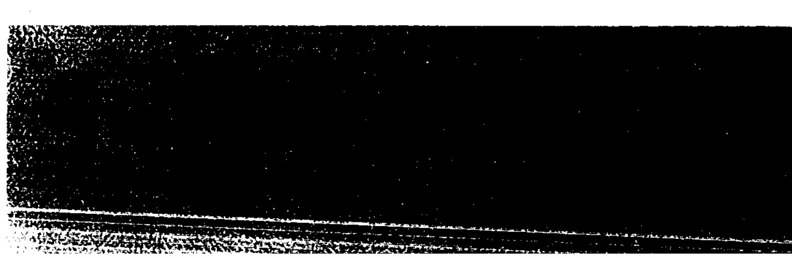
Technical Memorandum-21

OPTICAL IMAGERS FOR THE SMALL EARTH RESOURCES SATELLITE



Technical Memorandum-21

OPTICAL IMAGERS FOR THE SMALL EARTH RESOURCES SATELLITE

by

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for

Earth Resources Survey Program Office (SAR)
National Aeronautics and Space Administration
Washington, D. C.

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APPROVED:

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April 1967

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OPTICAL IMAGERS FOR THE SMALL EARTH RESOURCES SATELLITE

1. INTRODUCTION

The Earth Resources Survey Program, a relatively new NASA activity, is a complex program with requirements, objectives, operations, and parameters somewhat distinct from other space programs. As such, it is fair to surmise that sensors, data links, mission profiles, and instrumentation which have proven satisfactory in other space applications may not necessarily be equally satisfactory here. For this reason it is important that an analysis be undertaken to determine the best possible choice of parameters to insure success of this program.

This report, a look at imaging systems for Small Earth Resources Satellites, is envisioned as the first in a series of studies which, it is hoped, will lead to basic design goals for satellites and support systems to serve the Earth Resources Survey Program. Future reports will be concerned with, among other things, radar and infrared sensors, data storage and telemetry, and data relay and analysis techniques. Some of the spacecraft being considered for this program are shown in Table 1, and Table 2 lists candidate instruments for ERS A and B.

The acquisition of the Earth's resources by remote sensors in space requires a knowledge not only of sensor capability but also of sensor requirements, particularly with regard to resolution, in order to arrive at meaningful answers to spacecraft sensor selection. Table 3 indicates the relationship between sensor resolution and resources application, as well as demonstrating which resources may be studied for several ranges of ground resolution among the various disciplines. The selection is based on desired performance and does not reflect current instrument capabilities. However, it must be emphasized that to achieve low complexity and high reliability, remote sensing for ERS A and B should be confined to those techniques which are well within the state of the art. These include radar, IR, and photography - both TV and conventional.

This study has been limited to photographic techniques since they are the most advanced of imaging systems and data interpretation is considerably simpler than for other types of imaging systems. Tables 4 and 5 illustrate the functional requirements of a Small Earth Resources Satellite and the sensor requirements for this satellite, respectively.

A consideration of imaging systems suitable for use in small Earth-orbiting satellites must give primary importance to gross physical characteristics such as size, weight, and power requirements. An analysis of available instruments based on these constraints narrowed the field of candidate sensors to seven. These seven contending imaging systems were then evaluated with respect to system and sensor requirements. Examples of parameters which affect system performance and effectiveness are ground resolution, sensitivity, cost, map scale, data handling capability, and reliability. Perhaps most stringent of these are the requirements that the satellite function usefully for at least one year and provide 100-foot resolution. The implications are broad indeed: systems reliability and design must approach theoretical design limits and sensors using film must be capable of carrying film loads sufficient for a year's operation.

The conclusions reached in this study must be regarded as only tentative and are based solely on consideration of imaging systems. Formal recommendations will be made at the conclusion of these investigations.

2. OPTICAL REQUIREMENTS

All imaging systems share common acquisition optics regardless of the principle of image formation and ground recovery of data; whether images are formed on film or optically active surfaces, the image is in general flat and extended [1], and hence camera lenses are designed to produce a large flat image field. This requires that camera lenses be highly

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[1] Certain specialized cameras such as the panoramic are exceptions.

corrected for curvature of field, coma, chromatic aberration, astigmatism, distortion, and spherical aberration, the degree of correction being determined by the limiting resolution of the photosensitive surface. In practice, however, today's computer-designed optics and advanced fabrication techniques can produce lenses superior to the best film available. In general, lens selection is based on size of image format or total angular field of view and required exposure time per frame. For satellite-mounted cameras it is often necessary to introduce image motion compensation (IMC) to correct for the effect of satellite movement during frame exposure. This may be done by means of a moving slit in the focal place shutter or an alternate technique is to employ a rotating mirror. In either case the motion is opposite to that of the satellite.

The total angular field of view (FOV), because it is of central importance to any consideration of imaging optics, deserves some detailed treatment. Generally, one arrives at a value for the FOV for the acquisition optics by specifying the orbital altitude of the satellite and the ground coverage desired without considering whether the spatial resolution of the camera system is inherently good enough to accept the artificially imposed "look angle". The effective FOV of lenses is limited by apertures called field stops to eliminate poor imagery at the edge of the field. So-called wide angle lenses are specially corrected to eliminate aberrations at the edge of the field; however, these lenses are generally unsatisfactory for space-borne applications for reasons which need not concern us here. The inherent limitation in FOV of imaging systems is usually not so restrictive that performance goals can't be satisfied. Nevertheless, it is useful to know what the limiting FOV is for a given camera system. The built-in limits to a camera's FOV are established by the resolution of the photosurface (film or vidicon tube) and by the map scale. These are expressed quantitatively in the equation:

$$\theta \leq \frac{w}{F.L.} \tag{1}$$

where θ = Field of View (radians)

w = Film Width (inches)

and F.L. = Focal Length (inches).

The limitations mentioned above are not readily apparent in the above expression, but if the right-hand side of equation (1) were multiplied top and bottom by r, the resolution of the photosurface (expressed in line pairs per millimeter) [1], then the above inequality would appear as follows:

$$\theta \leq \left(\frac{1}{r \times F.L.}\right) (rw) \tag{2}$$

---

[1] Historically, there has been a difference of opinion on the expression of spatial resolution. Traditionally, optical specialists have utilized line pairs/mm. However, information content is best expressed by line elements/mm or cycles/mm where a cycle contains two bits of information. Since this report is intended primarily for user agencies, the more familiar notation of line pairs/mm has been retained.

where $(\frac{1}{r \times F.L.})$ is simply twice the angle a resolution element forms at the focal plane of the acquisition optics and (rw) is half the total number of resolution elements along a diagonal of the focal plane. Again, if equation (1) is now multiplied top and bottom by h, the orbital altitude (expressed in nautical miles), then it would appear as follows:

$$\theta \leq (\frac{w}{h}) (\frac{h}{F.L.}) \qquad (3)$$

where $\frac{h}{F.L.}$ is, by definition, the map scale [1]. The inequalities exhibited in these expressions are necessary and must be satisfied; they indicate that (a) the photosurface must not limit the system performance, and (b) the map scale must be chosen to give meaningful imagery.

Two examples are given to illustrate these points: to satisfy equation (2), suppose the resolution angle is 0.1 milliradian, the film is 70 mm (2-1/4 inch format), and the spatial resolution of the film is 100 line pairs per millimeter. Then

$$\theta \leq 1.1 \text{ rad} = 60°.$$

To investigate equation (3) assume h is 300 nautical miles and the map scale 1:5,000,000. Then

$$\theta \leq .52 \text{ rad} = 30°.$$

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[1] This is the acquisition map scale; useful map scale can vary from this through enlargement. Map scale may also be thought of as the ratio of the distance between two points on the ground object plane, to the distance between these same points in the lens focal plane (film).

Thus in this example, the limitation in FOV would be the map scale.

In addition to limitations in FOV, camera lenses impose certain other restrictions on imaging systems performance. As an aid to understanding the physical constraints imposed by acquisition optics, Figures 1 through 4 are included. These relationships are discussed in more detail in Appendix A. Figure 1 is a plot of ground coverage as a function of orbital altitude and field of view. We see that at an orbital altitude of 300 nautical miles [1] a camera lens must have almost a 30-degree field of view (26.5 degrees is the actual value) to survey a 100-mile swath on the ground. Figure 2 relates field of view to image format as a function of focal length. Hence, for a field of view of 26.5 degrees and a 7-inch focal length, the effective image frame size would be about 2.25-inches on a side, which is the format for 70 mm film. Figure 3 illustrates the dependence of ground resolution on system resolution as a function of focal length. Thus, to obtain a resolution on the ground of 100 feet with a 7-inch lens requires a system resolution of 52 line pairs per millimeter minimum. This means that the primary spatial resolution of the photo-detector should be about 80 line pairs per millimeter for systems which telemeter data to ground since a 25 to 40 percent degradation

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[1] The 300 nautical mile altitude is chosen as a compromise between resolution and lifetime requirements. Low altitude is desired for better resolution, but 300 nautical miles is needed for station-keeping and to overcome atmosphere drag to insure a one-year duration.

of signal occurs with such systems. Figure 4 plots acquisition map scale as a function of orbital altitude for typical focal lengths. The 7-inch lens cited above will have a $1:3.13 \times 10^6$ map scale at 300 nautical miles.

In general, the user of spacecraft imagery is interested in three quantities: ground resolution, map scale, and swath width. Knowledge of these enables him to make a quick evaluation of the system's overall performance. If these "performance figures" satisfy his requirements, then further evaluation is indicated involving such things as sensor reliability, data handling capability, cost, etc. Expressions for determining ground resolution, map scale, and swath width are given in Appendix A.

3. PHYSICAL AND PERFORMANCE CHARACTERISTICS OF CANDIDATE CAMERA SYSTEMS

When selecting instruments and sensors for satellite application, equally important with performance are such gross characteristics as weight, size, and power requirements. Table 6 lists these characteristics [1] for fourteen camera types. Satisfying the gross physical constraints of a small Earth-orbiting satellite reduces the list of candidate systems to six whose characteristics are given in Table 7. Some of these instruments may fulfill the minimum functional and sensor

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[1] Data shown are best available at time of compilation. Updating of parameters is a continuing process so that numbers cited in this and subsequent tables should be considered guides rather than hardened parameters. Most reliable data are, of course, those associated with operational systems.

requirements of Tables 4 and 5 after data degradation by telemetry.

Of the many variables associated with satellite sensors, the primary concern is resolution. Where cameras are concerned, ground resolution is the principal parameter. Table 8 lists ground resolution for the six sensors, based on current configurations. The resolutions have been normalized for an altitude of 300 nautical miles corresponding to a one-year mission life and 2:1 contrast ratio. One observes that the ground resolution varies by over an order of magnitude. The Advanced Vidicon Camera, although operational, is so far removed from the 100 to 300 foot resolution desired for the Earth resources satellite that it may be discounted without further consideration; it is included as a benchmark of what is operational today.

The normal tendency is to focus on the system having the highest resolution and make this the primary candidate instrument. In this instance, however, complications immediately arise. The Lunar Orbiter camera, with a 24-inch focal length has a potential ground resolution of 20 feet, but its film capacity in this operational configuration is only 200 frames - an unacceptable figure. This camera has a second lens with a 3-inch focal length and a ground resolution of 160 feet, still within the resolution requirements. Its film capacity using this lens exclusively is 1200 frames; but this is still too few to satify system requirements. It is probable that the film capacity can be increased for this camera package, but it would require redesign and redevelopment. It is impossible to say at this time what the ultimate capacity might be; however, it should be noted that the shelf life of the film is only guaranteed for three months according to the manufacturer.

The next instrument in order of resolution is the space TV system. An example of this system is an intensifier vidicon (TRW) with 1000 TV lines per frame. It is claimed that this sensor will have 100-foot ground resolutions[1]. The chief drawback to these systems is that at present they are only laboratory models or preliminary designs. A report was prepared in June 1966 on image-forming sensors that included a 2-inch return beam vidicon (RCA) and pointed out the potential of very high resolution (6000 lines) that may be obtained from such a tube. This report was presented to AGSTOMS[2] on June 9, 1966. Upon the recommendation of AGSTOMS, personnel from NASA's Goddard Space Flight Center prepared a work statement for the test and simulation of the 2-inch return beam vidicon. A proposal for accomplishing this work has been prepared, and the tests will be implemented in early CY 1967.

For the Gemini Hasselblad Camera it must be emphasized that the designated resolutions of 18 feet and 285 feet for focal lengths of 9.8 inches and 3.15 inches, respectively, must

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[1]At a contrast ratio of 1000:1 and without telemetry losses.

[2]Advisory Group for Supporting Technology for Operational Meteorological Satellites. This group includes representatives from NASA, ESSA, and DOD.

be regarded as only representative of the large number of lenses and film which can be used with this camera. The fact that color film was the film of choice helps explain the relatively low ground resolution - this film has perhaps 1/4 or 1/5 the spatial resolution of black and white aerial film. Nevertheless, it has been found that color highlights detail so that useful resolution is not as poor as indicated, and in fact, sometimes details are discerned in color which are not readily obvious in black and white. This cannot be expressed quantitatively however. In fact the Hasselblad could achieve resolutions even greater than the Lunar Orbiter camera system, using the same optics, because no degradations occur due to telemetry link and reconstruction. However, the Hasselblad's effectiveness is limited in the same way, namely, film capacity. What is required for effecting long missions is film bulk, and in the case of the Hasselblad, some way of retrieving the film.

An interesting imaging system is the Spin-Scan Camera used aboard the Applications Technology Satellite in synchronous orbit. This imager uses a 5-inch Cassegrain telescope as the objective, and its 0.1 x 0.1 milliradian instantaneous field of view illuminates a photomultiplier. The camera spins at the rate of 100 rpm and scans 100 horizontal lines every minute. It requires 20 cycles to produce a 2,000 scan-line frame. Although the optics of this sensor are unconventional, perhaps unique among satellite imagers, the frame rate writing time of 20 minutes is so slow as to render it unacceptable for low-altitude Earth resources applications.

The last imaging system to be considered is the Dielectric Tape Camera. This instrument uses a tape substrate on which are deposited layers of conducting material, photoconducting material, and dielectric. The tape is operated in a vacuum environment and behaves very much like the photocathode of a storage tub; and like a storage tube, there are three electron guns for writing, reading, and erasing. At present this system has a resolution of only 445 feet. The spatial resolution of this film is limited by the physical constraints of the writing process which will be discussed later. At present the spatial resolution of the tape is 12 line pairs per millimeter. In its configuration as a panoramic camera, its ground resolution of 445 feet is less than half as good as some other Earth resources imaging sensors; however, the theoretical limit of spatial resolution has not yet been reached, and one may expect further progress in the future. Since even a doubling of the resolution capability would make this instrument a serious contender for the Earth resources project, any further improvement in resolution could be of great significance.

4. DISCUSSION

Of the seven candidate imaging systems which are physically capable of being operated in an ERS A and B environment, two may be eliminated as being either too poor in ground resolution or having too slow a framing rate. Of the five remaining, three systems are electro-optical, one is photo-optical, and the fifth, a hybrid, combines photo-optical, electro-optical, and electronic concepts. These five systems must now be evaluated with respect to system complexity, effectiveness, data handling capability, power requirements, and bulk.

Figure 5 is an example of the type of parametric analyses required for selecting an imaging sensor system for the Earth resources satellites. The curves are based on optics with 8-inch focal length and 70 mm film. Where conflicting demands must be satisfied, a unified approach can result only from comparison and evaluation of all possible alternatives. The parameters shown here are but a few of the total number vying for consideration.

The figure illustrates how map scale and ground resolution deteriorate with increasing orbital altitude, whereas satellite lifetime and film weight improve with increasing altitude. Therefore, if a primary requirement is a one-year useful satellite life, then a minimum value is placed on orbital altitude, and all other parameters consequently also receive limiting values. However, if the system cannot accommodate any of these limitations, then lifetime adjustments may be necessary. Thus by matching requirements and capabilities based on parametric considerations, a practical compromise is achieved.

4.1 Photo-Optical Systems

A photo-optical imager, such as the Hasselblad camera, is by its nature a unidirectional or nonreversible system.

That is to say, images are recorded on a nonreversible medium so that once made,a fresh film surface must be presented for a new image to be recorded. Therefore, for a system to operate for a year requires a substantial quantity of film and a means for delivering the film to the ground. Of course a question arises as to whether continuous synoptic coverage for a year is actually desired or required on the initial flights. With an Earth land mass of about 43,000 square nautical miles, a picture frame encompassing a 100 nautical mile swath on a side would require 4300 frames for a single total global coverage. This is equivalent to about 900 feet of 70 mm film and weighing about 7 pounds, a quantity easily stored aboard a small Earth resources satellite. The quality (resolution, S/N, spectral sensitivity) of the returned film is unsurpassed by any other imaging system. Based on the Gemini experiment with synoptic terrain photography, 900 frames of high resolution imagery contain enough data to keep investigators busy for several years [1].

It is difficult to predict what the ultimate film capacity of a small Earth satellite might be. However, if Nimbus

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[1] In the Gemini experiment about 1100 useful photographs were obtained and the principal investigator estimates it will take 2 to 3 years to sift all the frames. Approximately 300 useful photographs were returned by the first two Lunar Orbiters, and these 300 frames are keeping upwards of thirty investigators busy full-time and will probably do so for several more months. Another aspect of the data analysis problem is the extent of the analysis. For basic photographic or topographic maps, a level of 4000 to 12,000 synoptic photos probably could be handled per year. However, for detailed interpretation of test-site photos, the Earth Resources Survey investigators will be saturated at a much lower level.

is taken as representative of this class of vehicle, a "ball park" effort at establishing its film load may be attempted. Based on a scaling of Department of Defense vehicles, a Nimbus Satellite among the largest of the ERS A and B type spacecraft might be modified to carry a 100 pound reentry vehicle with 25 pounds of 70 mm film - equivalent to about 3.5 world land coverages. Film recovery via a reentry vehicle introduces operational complexity but is currently being accomplished successfully.

4.2 Hybrid Systems

The next camera type, of which the Lunar Orbiter camera is representative, is a combination photo-optical and electro-optical device. This system contains a conventional camera in the front end. After exposure the film is developed by the Bimat process; the developed frame is then scanned electro-optically and the data telemetered to ground stations. With a conventional camera in the loop, there arises the same problems with film bulk previously described. Here the problem is compounded because, for each length of negative paper, there must now be an equal length of positive paper plus a layer of developer. At the very least, the total film bulk is doubled so that for a given film budget the number of frames is half of that available with a photo-optical camera without onboard processing. This arrangement works out better with regard to film weight and operational complexity since the satellite does not have to carry along a reentry vehicle; however, it does carry telemetry equipment.

The Boeing version of the Lunar Orbiter in its present configuration is limited to 1200 frames with a ground resolution of 157 feet. A modification to increase the film capacity and resolution would entail a substantial packaging and design effort but is technically feasible. One advantage of this system over the pure photo-optical camera is its limited "realtime" processing of data. On the debit side are the time and costs involved in modifying the system, the relatively short shelf life of the Bimat film, the fact that the film must be advanced periodically which may complicate programming, and also the fact that this is inherently a more complex payload.

4.3 Electro-Optical Systems

TV systems, using vidicon tubes as the sensor element, do not produce received images having qualities equal to those from photo-optical devices. There are several conversion processes - vidicon image to electron beam to tape to electronic signal to radio signal and with the process reversed at the ground station to obtain an image. As a result of all these steps, perhaps as much as 25 to 40 percent degradation in spatial resolution occurs relative to the basic detector performance with corresponding loss in contrast, spectral resolution (loss of gray scale), S/N, and so forth.

Serious as these losses are, these systems nevertheless have promise of producing good quality images; but one must remember that the photographic resolution obtained on the ground is not equivalent to the spatial resolution at the vidicon. For example, if we consider the proposed TRW vidicon, having a nominal spatial resolution of 1000 lines and sweeping a 16 nautical mile swath (it uses six vidicon tubes to obtain a 96 nautical mile swath), the minimum number of resolution elements required to give a 100-foot ground resolution is 960. But we must expect at the very least a 25 percent degradation to occur in image quality due to telemetry and a further 25 percent degradation at a 2:1 contrast ratio so that the 1000 scan lines on the vidicon become effectively no more than about 560 lines when reconstructed on the ground. As a result, the nominal resolution at the sensor translates to, at best, a 170-foot resolution on the ground. The RCA system fares no better. Assuming that they may achieve an effective spatial resolution of 6000 lines at the vidicon, the number of resolution elements required for a 96 nautical mile swath is 5760, so with an upper limit of 4500 lines at a 2:1 contrast ratio and 25 percent telemetry degradation, the ground resolution, at best, will also be 170 feet.

TV imaging systems may enjoy an advantage over pure photo-optical systems with regard to system weight; both the RCA and TRW systems weigh less than estimated previously for an equivalent photo-optical system with reentry vehicle. Another advantage of TV imaging systems is their potentially long useful lifetimes. For example, their operational life is not rigidly predetermined by their film storage capability. With adequate testing and redundancy to provide good reliability, these systems would be able to function as long as the satellite remains in orbit. The weakest link in the data processing chain is the tape recorder which in the past has proven to be less than completely reliable. Still another advantage is the "realtime" data processing capability inherent in electro-optic and electronic systems.

The chief disadvantage of TV systems is the complexity of onboard and ground support equipment, which is reflected in the costs. Also the need for ground station support implies operating on a time-sharing basis which may hamper or delay data acquisition.

The Dielectric Tape Camera appears as a likely alternative. The dielectric tape is optically active and the image is stored directly on the tape through the simultaneous interaction of electron beam and optical input on its surface. The dielectric tape camera, an electro-optic and electronic device, generally possesses the same characteristics and advantages of similar systems such as the TV camera: it is compact and lightweight, processes data in realtime and is unique in not requiring a separate recorder.

The greatest drawback to the use of the dielectric tape camera for Earth resources applications is its relatively poor resolution, which is caused by the method of writing or "imaging" on the dielectric tape. In order to "write" on the tape, it is necessary to pass an electron beam and optical input through a thin slit. As is the case with slits, when it becomes thin enough, it starts to diffract light as well as electron beams. Any diffraction effects would act like noise and degrade the signal; the smaller the slit is made, the stronger becomes the diffraction. For the electrons space-charge buildup resulting from too narrow a slit could cause serious anomalies at the film plane. Specially designed electrostatic "slits" are employed to relieve this problem and generally work very well. For the light signal, too narrow a slit would leave the zero diffraction order with little energy, the bulk of the light energy going into the neighboring diffraction orders.

Diffraction problems arising from light passing through narrow slits are generally more difficult to cope with.

It is not unrealistic to expect improvements in the spatial resolution of dielectric tapes as technical advancements are made. For example, RCA has considered a 70 mm format. When the resolution of the dielectric tape camera approaches that of TV systems, it is almost certain to become a leading contender for Earth resources applications because it is inherently a simpler system than TV.

4.4 Estimates for 1970 Systems

The difficulty in comparing the present Hasselblad, Dielectric Tape, and Lunar Orbiter camera systems with the "Advanced TV" system is in the degree of development between these imaging systems. The "Advanced TV" systems using return beam vidicon sensors and high data rate recorders are under development and proposed for the 1969-1970 time frame, whereas no "advanced" planning has been considered for the other camera systems although performance improvement is clearly possible. In this section an attempt is made to estimate what this performance might be in 1970 to provide a more meaningful and equitable comparison. The "systems" considered here include recorders and transmitters where applicable.

The following assumptions have been used in establishing a comparison:

a. 300 nautical mile altitude

b. 100 mile swath width

c. 6 minutes/orbit/transmitter average transmission time (2 ground stations with two receivers each).

d. Resolution in line pairs/millimeter using 2:1 contrast and telemetry degradation.

e. Land coverage at 100 by 100 nautical miles is 4300 photos.

Certain improvements were considered. The conventional camera would use the latest high-quality film with matching lenses to provide 180 line pairs/millimeter in black and white or 90 line pairs/millimeter in color. The reentry container would carry 15 pounds of film (9000 frames). Using a 300 nautical mile altitude, a 100 nautical mile swath width, and 70 mm film, the focal length is 6.75 inches.

The Dielectric Tape camera would be 70 mm, would have a spatial resolution of 25 line pairs/millimeter (which RCA believes is possible), and would use 6.75-inch focal length optics. The transmission link is assumed to be 4MHz.

The Lunar Orbiter camera system would have improved lenses, reader, and transmitter to fully utilize the film capability and produce a system ground resolution of 150 line pairs/millimeter. A 6.75-inch focal length also would be used. The two cameras would have a total of 30 pounds of improved Bimat film (6000 frames), properly shielded and temperature-controlled to give one-year operation. Two modes are considered: in the first the two cameras are aimed side-by-side in a fore and aft direction to give 100 mile swath width by

200 miles long in black and white; in the second the two are overlapped to give 100 miles by 100 miles and 2 colors. Each transmitter is assumed to have a capability of 4 MHz.

The average realtime readout for each sensor/transmitter combination is calculated from:

$$\text{No. frames/orbit} = \frac{\text{Bandwidth x transmission time}}{\text{Bits/frame}}$$

$$\text{Bits/frame} = (2 \times \text{line pairs/mm} \times \text{format})^2 \times 5$$

where the 5 is for grey scale (15 shades of grey) and parity check.

The number of coverages is approximated by the number of frames per year times the area of each frame divided by the land area (43×10^6 square nautical miles). This assumes no overlap and theoretically would require a complex photo program, but the approximation is adequate for this analysis.

The characteristics on which the projection was based are given in Table 9. The parameters of interest for comparison are summarized in Table 10. It can be seen that the Conventional camera with black and white film and the improved Lunar Orbiter camera system, while heavier, have the best resolution (60 to 70 feet) with good map scale ($1:3.2 \times 10^6$) and with modest coverage (0.8 to 3.5 times). The Lunar Orbiter camera system can provide 18 pictures per day while the Conventional camera has no realtime readout capability. The improved Dielectric Tape camera is superior to the Advanced TV system in both coverage and map scale. However, the Advanced TV system does provide two colors and greater resolution (340 versus 420 feet).

Qualitative estimates of the schedules and costs for these advanced systems have been made. These statements are rough estimates which require verification and are summarized in Table 11.

5. CONCLUSIONS

Based on the projections for 1970, the user requirements, and the capabilities of ERS A and B one can conclude that:

- If there is no requirement for realtime data return, the reasonable Earth coverage and minimal development requirements of the conventional camera would appear to make it the preferred system.
- If there is a requirement for realtime data return, the resolution and two color capabilities of the advanced TV system would seem most desirable.
- That final decisions should include consideration of data management problems (acquisition and relay), reliability, and improved total system cost information.

The relative merits of each system have been qualitatively compared in Table 12. These ratings serve only to illustrate the comparison on the basis of individual performance and physical parameters. Since the emphasis of any parameter in a total decision is both subjective and dependent on the specific application, the table should not be used quantitatively to obtain a choice of systems.

Table 1

SPACECRAFT FOR THE EARTH RESOURCES SURVEY PROGRAM

Spacecraft Designation	Apollo Applications Program	Small Earth Resources Satellite (ERS A and B)	Medium Earth Resources Satellite (ERS C and D)	Large Earth Resources Satellite (ERS E, F, G)
Spacecraft weight (lb)	30,000-90,000	800-1,200	3,000-5,000	20,000-30,000
Spacecraft class	Multiman	Nimbus/Tiros	Orbiting Astronomical Observ.	New automated
Instrument weight (lb)	4,000-6,000	200-400	600-1,000	4,000-6,000
Candidate instruments	Full complement of instruments: Cameras, radars, microwave, IR, UV, magnetic, gravity	Visible and infrared TV, imager, data relay, scatterometer	Cameras, TV, IR, UV, magnetic, data relay	Full complement of instruments: Cameras, radars, microwave, IR, UV, magnetic, gravity
Launch vehicle	Saturn IB, Saturn V, or 260/SIVB	Thor/Delta or Agena	Atlas/Agena	Saturn IB or 260/SIVB class

Table 2

CANDIDATE INSTRUMENTS FOR SMALL EARTH RESOURCES SATELLITES (ERS A AND B)

Function	Candidate Instrument	Estimated Weight (lb)	Estimated Power (watts)	Spectral Range	Antenna	Spatial Resolution [1]
Imager	2-3 TV cameras (new 2-inch vidicons)	200	100-200	4500-9000 Å	None	100-400 feet
Data relay	Interrogation, recording, location system (IRLS)	25	127	400 MHz	UGF blade	6000 feet [2]
Scatterometer	Radar	25	15	1200 MHz	13 ft inflatable array	24 miles

1 From 300 nautical miles altitude.

2 Accuracy to which position of ground transmitter is known.

Table 3

NATURAL RESOURCE APPLICATIONS GROUPED BY RESOLUTION REQUIREMENTS [1]

Spatial Resolution[2] (meters)	Agriculture/ Forestry	Geography	Geology	Hydrology	Oceanography
<20	Timber-, water- and snowline studies Grass, brush, & timberland interfaces Vegetation density Tree count Tree crown diameter Crop species Crop acreage Irrigation studies Fields of smaller sizes, 10 acres or less Livestock census	Population & cultural studies Fishing boat activities Land use studies Topo-mapping 1:250,000 and larger scales Plant cover & soils Forest types Thematic mapping	Delineation of small folds Delineation of small linear elements Delineation of stratigraphic sequences Lithologic units Soil compaction Slope stability Permeability studies Ore deposits Local geothermal anomalies Tectonic studies Glaciological studies (local)	Groundwater discharge Subaqueous features of lakes Detection of water pollution, inland areas (rivers, lakes, bays) Effluents of major rivers Monitoring lake & reservoir levels Evapotranspiration Water surface roughness Rainfall Salt content Drainage basins Water regimens of valley glaciers Snow surveying Reservoir sedimentation	Ice surveillance Snow/ice & ice/water interface studies Wave profile Shoals & coastal mapping (bottom topography) Currents (long shore) Coastal marine processes (tidal variations) Estuarine & shoreline morphology Sea level & sea slope Sea mammals

[1]Requirements submitted by agencies and representatives of the various geoscience disciplines involved.

[2]Resolution (side dimension in meters of resolvable objects) is here defined as the ability to resolve Earth-surface distances per line pair at a target contrast of 2:1 under actual flight conditions.

Table 3 (Cont'd)

Spatial Resolution (meters)	Agriculture/ Forestry	Geography	Geology	Hydrology	Oceanography
20-100	Timber- & snowline studies Fields of larger sizes, 10 acres or more Soil temperature Detection of forest fires	Water resources Gross cultural studies Geomorphology studies Gross land use studies Topo mapping, scales smaller than 1:250,000 Pollution (air, land, water) Thematic mapping	Delineation of folds and linear elements Soil compaction Slope stability Gross geothermal studies Geomorphic studies Glaciological studies Mineral belts Permafrost	Evapotranspiration Water surface roughness Rainfall Salt content Drainage basins Water regimens of valley glaciers Snow surveying Reservoir sedimentation	Sea surface thermal mapping Cold region thermal structure Fresh/salt water interface Water pollution, large areas, oceanic, harbor areas Ocean waves Currents (offshore) Biological studies (fish & other populations) Wave refraction studies Volcanic activity
100-300	Timber-, snow- & desertline studies Fields of gross sizes (rangelands, etc.)	Land use studies Thematic mapping	Delineation of large folds Delineation of linear elements Lithologic units Geothermal studies Volcanic studies Metallogenic provinces Inventory of ice features	Evapotranspiration Water surface roughness Rainfall Monitoring lake & reservoir levels	Currents (offshore) Water masses Upwelling areas
>300	Soil moisture	Cloud studies Land use studies Thematic mapping	Delineation of large folds & faults Slope stability	Evapotranspiration Rainfall Snow surveying	Sea state Delineation of pack & cap ice margins Sea water color analysis

Table 4

FUNCTIONAL REQUIREMENTS
FOR SMALL EARTH RESOURCES SATELLITE

1. MINIMUM ONE YEAR USEFUL LIFETIME
2. REPETITIVE COVERAGE NEARLY GLOBAL IN EXTENT
3. REPETITIVE COVERAGE AT SAME LOCAL TIME
4. GROUND-BASED COMMAND
5. VERTICAL AND OBLIQUE VIEWING, $\pm$ 1° STABILIZATION
6. SPECTRAL SENSING FROM 0.35 TO 13 MICRONS
7. DATA RELAY FROM SURFACE SENSORS
8. INSTRUMENT GROWTH CAPABILITY OF 100 POUNDS
9. FLIGHT IN 1969 OR 1970

Table 5

SENSOR REQUIREMENTS
FOR SMALL EARTH RESOURCES SATELLITE

1. GROUND RESOLUTION: 300 FEET MINIMUM; 100 FEET PREFERRED

2. TONE: GRAY SCALE - 16 SHADES, COLOR PREFERRED IN SOME CASES (5 BITS, INCLUDING 1 PARITY)

3. SWATH WIDTH: 100 NAUTICAL MILES

4. WEIGHT: 400 POUNDS MAXIMUM INCLUDING ALL DATA PROCESSING INSTRUMENTATION; LESS THAN 200 POUNDS PREFERRED

5. SINGLE GROUND COVERAGE:

	Area	No. Frames @ 100 x 100 N.M.
ALL LAND	43×10^6 sq.N.M.	4,300
ENTIRE EARTH	105×10^6 sq.N.M.	10,500

6. MAP SCALE: 1:5,000,000 MINIMUM; 1:1,000,000 PREFERRED

7. AVAILABILITY: 1970 REQUIRED; 1969 PREFERRED.

Table 6

GROSS CAMERA CHARACTERISTICS

Camera Type	Project	Weight[1] (lb)	Size (cu.ft.)	Power (watts)
Low altitude panoramic	Aircraft	355		860(peak)
High altitude panoramic	Aircraft	743		120
Ultra-high resolution panoramic	Aircraft	700	100	50
High resolution panoramic	APP - B	300	20	50
Hasselblad	Gemini	1 to 100		
Metric	APP - B	300	45	500
Multispectral tracking telescope	APP - D	900	50-100	900
Synoptic multiband	APP - A	250	3.6	50
Advanced vidicon camera system	Nimbus	63 [2]	--	--
Dielectric tape	Nimbus	83 [3]	0.61	45
Spin-scan camera	ATS	35 [2]	--	6.5
TV systems-present AVCS	Vela	64	--	90
TV systems-future		150	2	70
Bimat camera	Lunar Orbiter	143 [3]	1	80

[1] For film-type cameras, weight shown is for camera only, without film.
[2] For TV systems, weight excludes recorders, transmitters, power supply, and programmer.
[3] Excludes transmitters, power supply, and programmers.

Table 7

PHYSICAL CHARACTERISTICS OF SELECTED CURRENT IMAGING SYSTEMS

Physical Characteristic	Imager Weight, pounds	System Weight, pounds	Power Requirements, watts	Data Transmission Bandwidth, Mc	Image Format	Focal Length, in.	f/number	Number of cameras
Advanced vidicon camera	63	190	?	1.5	0.44" x 0.44"	0.67	4-16	3
Hasselblad camera	3 4	200	-	-	70mm x 2.25"	3.15 9.8	1-22	1 1
ATS spin-scan camera	35	100	6.5	4	0.62" diam	9.25	1.9	1
Lunar Orbiter camera	143	170	80[1]	2.3	2.57" x 2.165" 8.62" x 2.165"	3 24	5.6 5.6	2
Dielectric Tape camera	83	160	45[1]	0.7	0.726" x 9.3"	6.7	1.9	1
TV system	22 64	150 190	20[1] 65[1]	4 2	2" x 1" 1" x 0.44"	5.1 10	3.5 2.0	2 6

[1]Camera package including data processing and telemetry.

Table 8

PERFORMANCE CHARACTERISTICS OF SELECTED IMAGING SYSTEMS

Performance Characteristic	Sensor Ground Resolution[1], feet @ 300 nautical miles	Map Scale, x 10^6	Swath Format, N.M.	Spectral Sensitivity, microns	Spatial Resolution[1], line pairs/mm	Contractor	Sensor Status
Lunar Orbiter camera	160 20	7.3 0.91	256 x 216 108 x 27	Film - B&W	110 80	Eastman Kodak	Op.
TV system	80 110	4.3 2.17	60 x 60 11 x 16	2-color	88 33	RCA TRW	U.D. U.D.
Hasselblad camera	285 18	6.95 2.23	200 x 200 70 x 70	Film - Color or B&W	40 (color) 205 (B&W)	Hasselblad	Op.
ATS spin-scan camera	70	0.237	85 x 85	0.47-0.63 Filter limited	55	Santa Barbara	Op.
Dielectric Tape camera	445	3.27	44		12	RCA	U.D.
Advanced vidicon camera	1530	32.7	140 x 550	0.35-0.8	35	RCA	Op.

[1]At photo element. This is only an indication of system potential. Resolution shown is with optics as currently used and not optimized for 300 nautical miles; contrast ratio of 2:1; no telemeter losses.

Op. = Operational
U.D. = Under Development

Table 9

SYSTEM CHARACTERISTICS

Imaging System	Optics Focal Length (inches)	Nominal Sensor Format	Number of Sensors	Number of Transmitters
Conventional camera	6.75	70 mm	1	-
Dielectric Tape camera	6.75	70 mm	1	1
Advanced TV	3	2 in.	2	2
Improved Lunar Orbiter camera	6.75	70 mm	2	2

Table 10

ESTIMATED 1970 PERFORMANCE CHARACTERISTICS FOR OPTICAL IMAGING SENSORS

Candidate Imaging System	System Ground Resolution* (feet)	System Weight (lb)	Map Scale (x 10^6)	Number of Land Coverage	Spectral Sensitivity (microns)
Preferred performance	~100	--	1.0	Many	0.3-13
Required performance	300	--	5.0	Several	B&W
Conventional camera - B&W	60	220	3.2	3.5	B&W
Conventional camera - Color	120				0.35-0.85
Dielectric Tape camera	420	160	3.2	27	B&W
Advanced TV	340	150	7.3	19	2-color overlay
Improved Lunar Orbiter camera - B&W	70	260	3.2	1.4	B&W
Improved Lunar Orbiter camera - 2-color	70		3.2	0.8	2-color overlay

*Based on line pairs.

Table 11

DEVELOPMENT PLAN

System	Operational Complexity	Technical Complexity	Schedule (months)	System Cost	
				Development	Procurement
Conventional camera	Complex	Simple	12	Modest (reentry vehicle)	Modest
Dielectric Tape camera	Simple	Medium	20	Modest	Modest
Advanced TV	Simple	Complex	24	Expensive	Expensive
Improved Lunar Orbiter camera	Simple	Very complex	18	Expensive	Expensive

Table 12

QUALITATIVE COMPARISON OF PROJECTED IMAGING SYSTEMS

System	Ground Resolution	Repetitive Coverage Factor	System Weight	Operational Complexity	Schedule	Total System Cost
Conventional camera	1	3	3	4	1	2
Lunar Orbiter camera	1	4	4	3	2	1
Dielectric Tape camera	3	1	1	1	2	4
Advanced TV	2	2	1	2	3	4

Evaluation Scale: 1 - 2 - 3 - 4: Most favorable - least favorable.

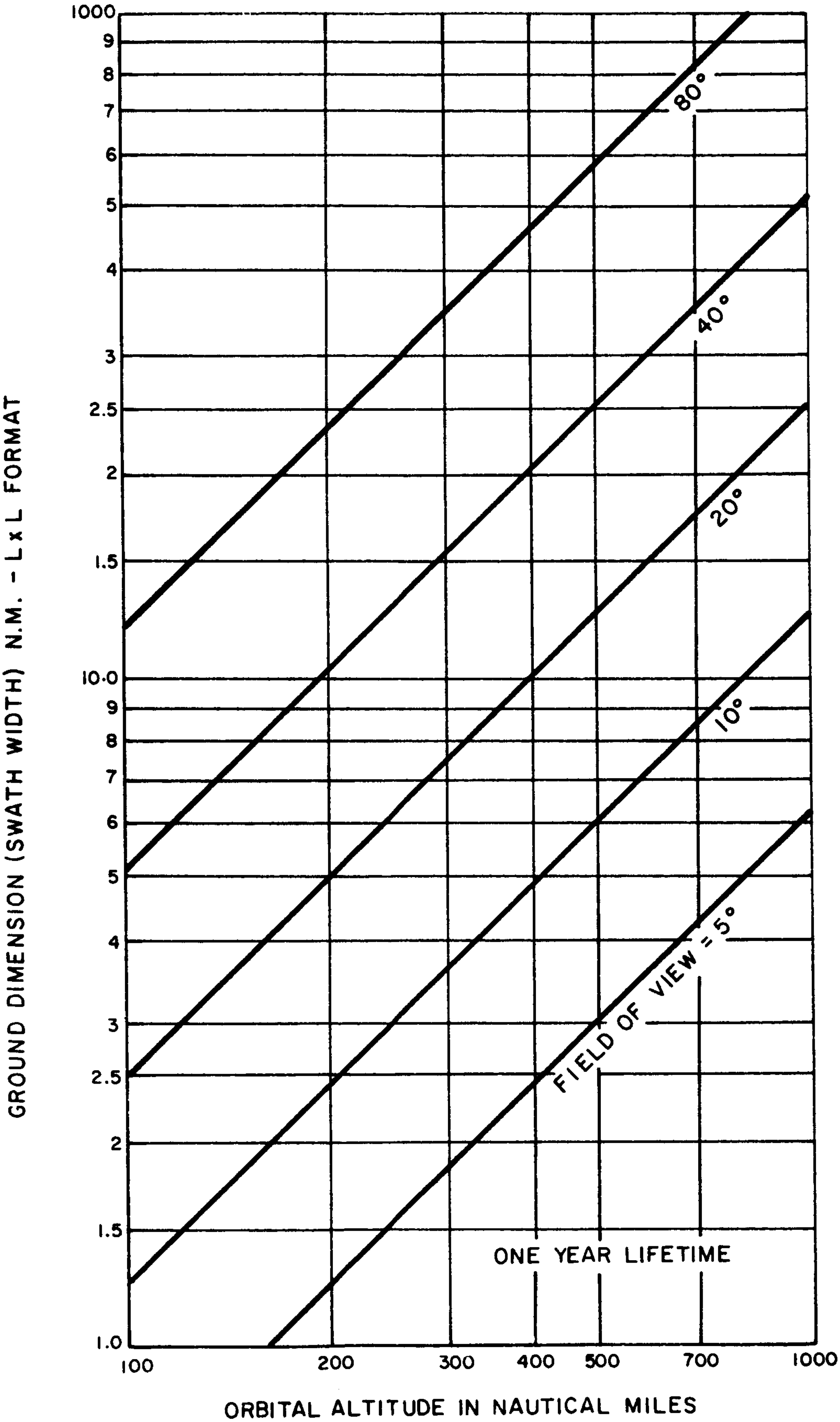


FIGURE I. SWATH WIDTH VS. ORBITAL ALTITUDE FOR TYPICAL FIELDS OF VIEW.

IITRI / ASC

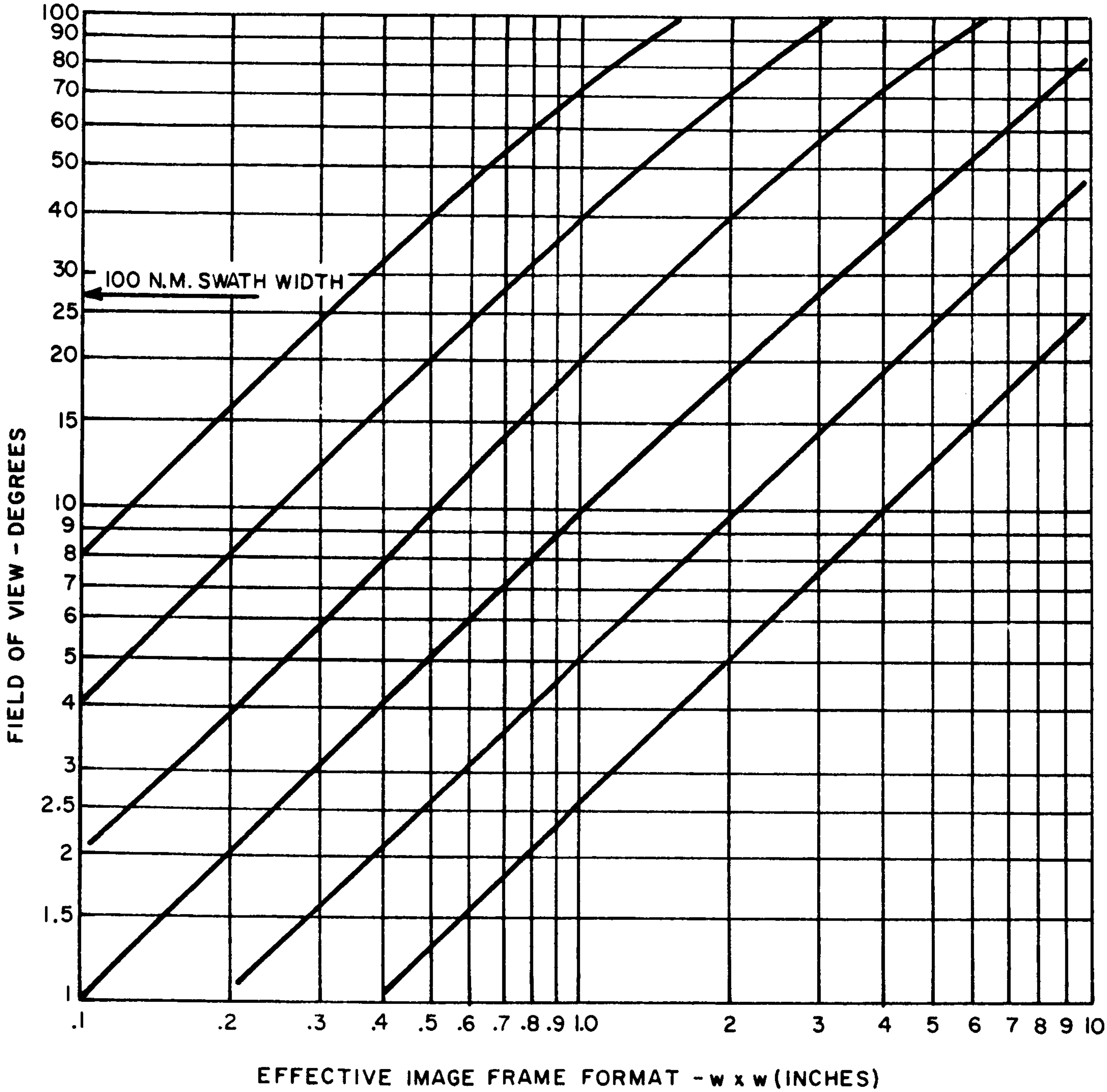


FIGURE 2. FIELD OF VIEW VS. IMAGE FORMAT

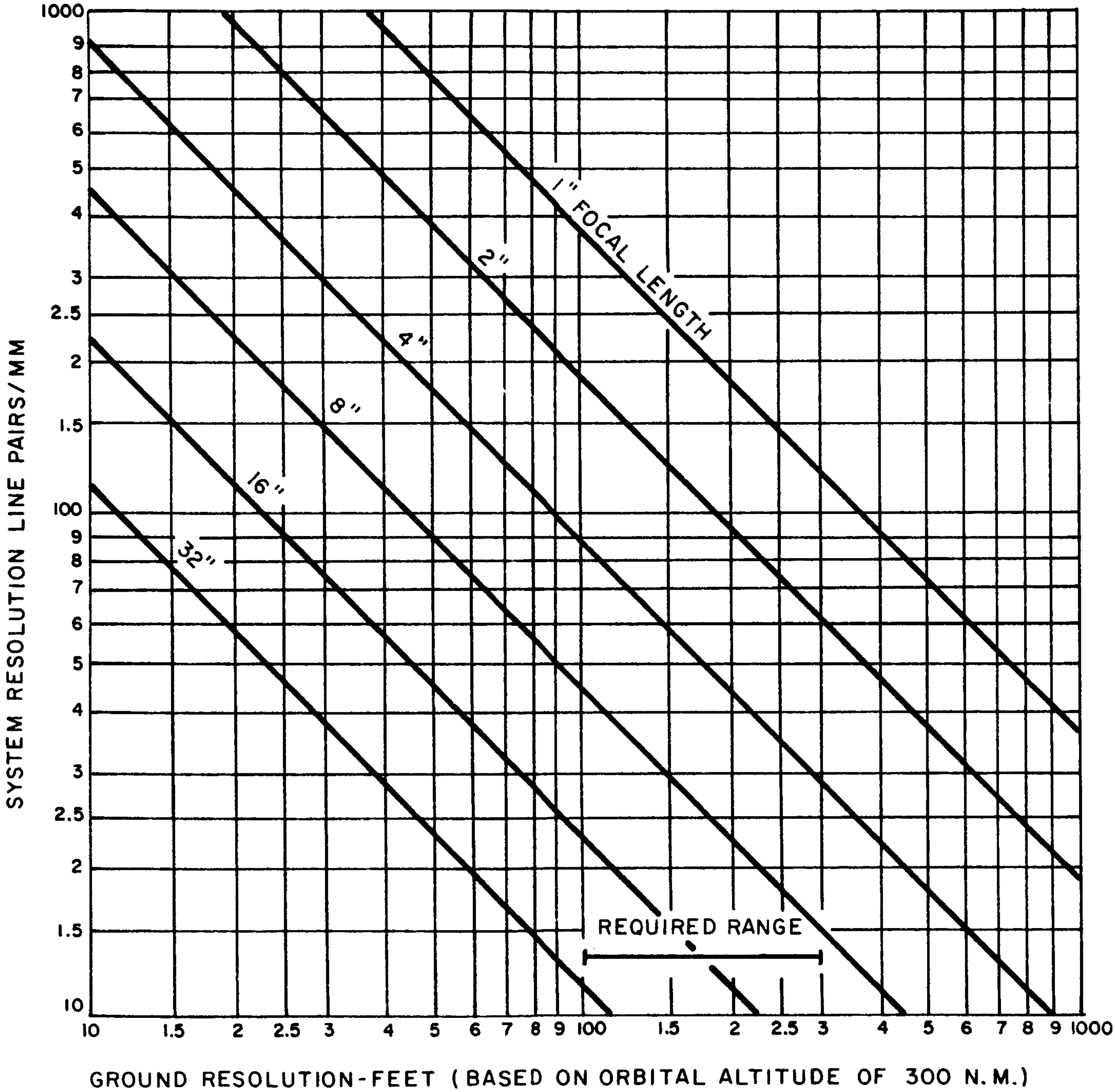


FIGURE 3. GROUND RESOLUTION VS. SPATIAL RESOLUTION FOR REPRESENTATIVE FOCAL LENGTHS.

IITRI/ASC

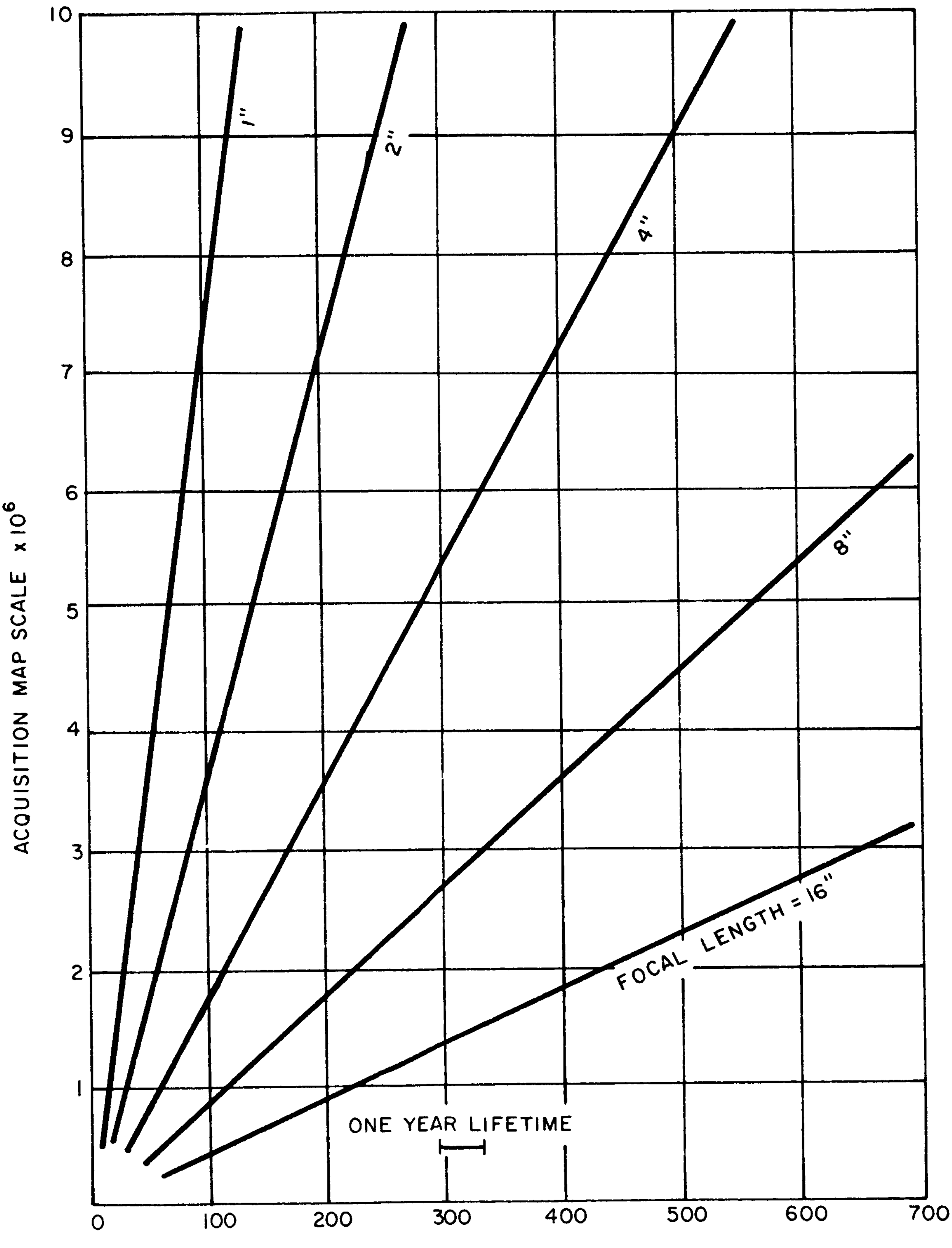
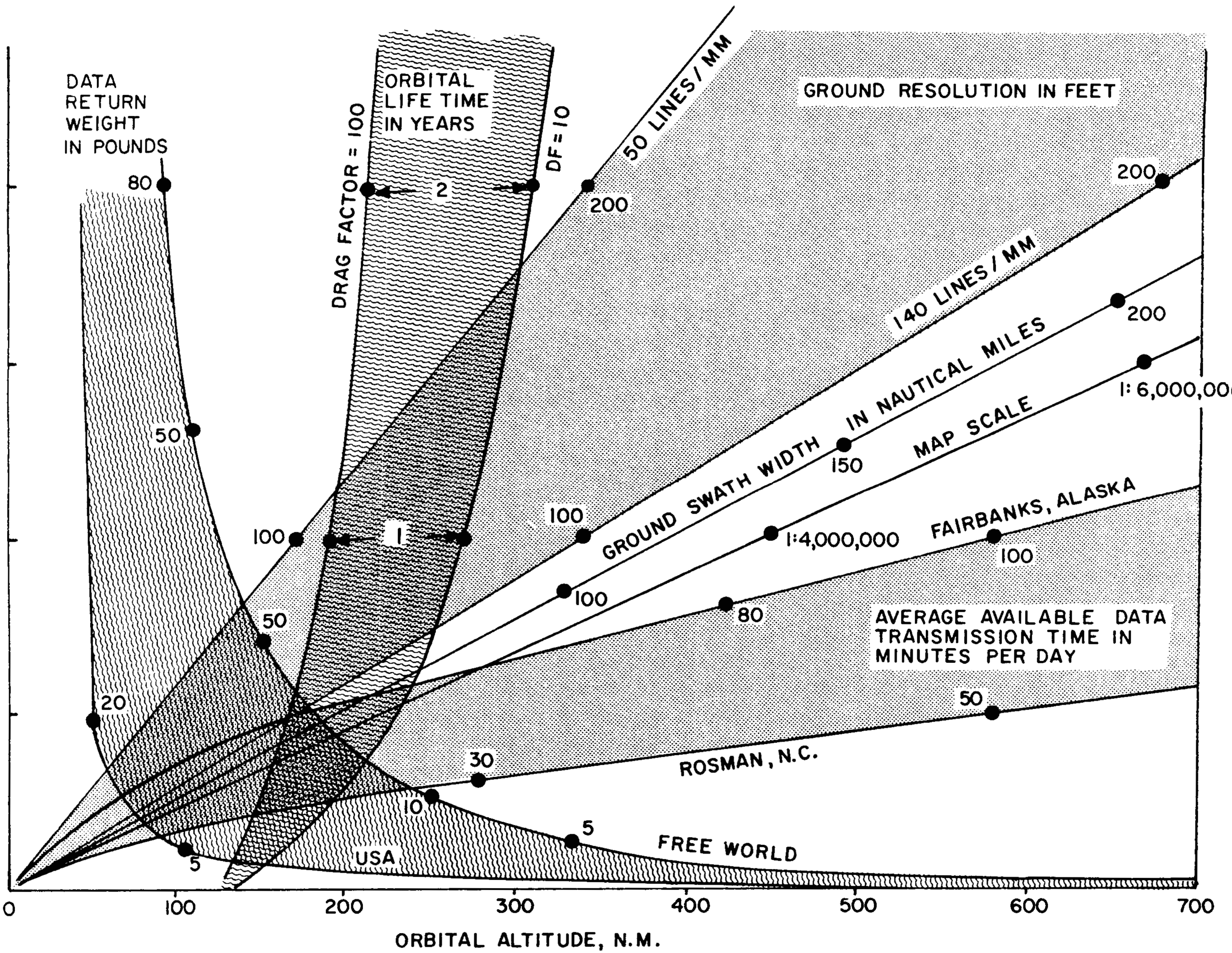


FIGURE 4. MAP SCALE VS. ORBITAL ALTITUDE

IITRI/ASC



GRAPH BASED ON 8 INCH FOCAL LENGTH CAMERA USING 70 MM FILM

FIGURE 5. THE EARTH RESOURCES SURVEY MAPPING PROBLEM CHOICE OF ALTITUDE IS A COMPROMISE

IITRI/ASC

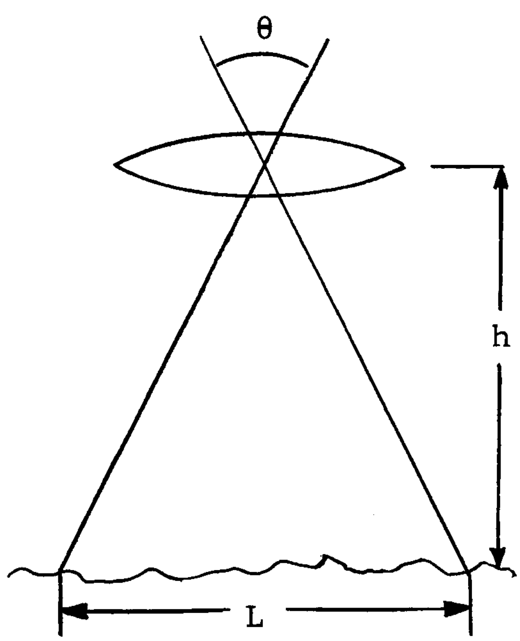
Appendix A

PARAMETRIC RELATIONSHIPS FOR ACQUISITION OPTICS

Appendix A

PARAMETRIC RELATIONSHIPS FOR ACQUISITION OPTICS

The relation between ground coverage, field of view, and orbital altitude is shown below:

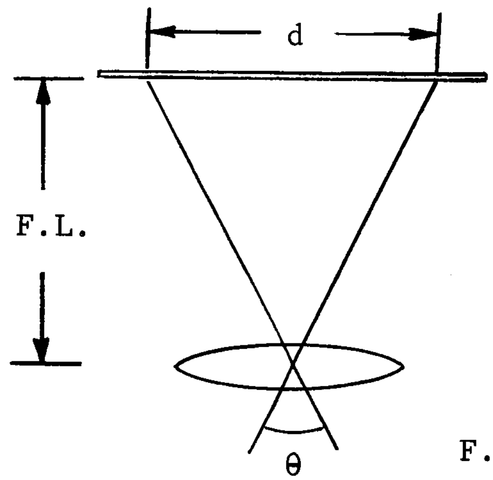


$$\theta = 2 \tan^{-1} \frac{L}{2h}$$

θ = field of view
h = altitude
L = diagonal of 1 x 1 ground swath

Figure A-1

The relation between field of view, image format, and focal length is illustrated in Figure A-2.

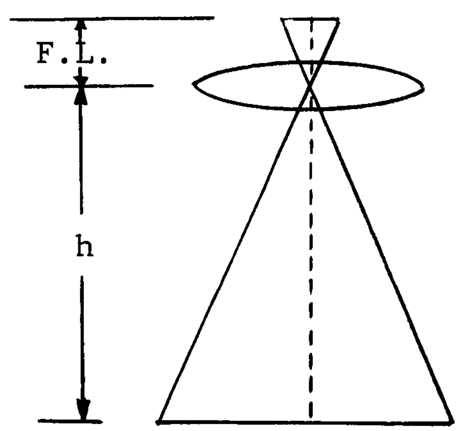


$$\theta = 2 \tan^{-1} \frac{d}{2F.L.}$$

θ = field of view
F.L. = focal length
d = diagonal of wxw film format

Figure A-2

Figure A-3 illustrates relation between ground resolution, spatial resolution of photo surface and focal length-orbital altitude is held fixed at 300 N.M.



$$G.R. = \frac{3.59 \times 10^4}{S.R. \times F.L.}$$

G.R. = ground resolution
S.R. = spatial resolution in line pairs/mm
F.L. = focal length in inches

Figure A-3

Map scale is defined by the expression

$$M.S. = \frac{\text{Orbital altitude}}{\text{Focal length}}$$

$$= \frac{7.3 \times 10^4 \times h}{F.L.}$$

where h = orbital altitude in N.M.
F.L. = focal length in inches.

Figure A-4 is a nomograph to bring together the pertinent parameters pertaining to acquisition optics for satellite imaging systems. Any three parameters, one being a function of the other two, may be related, the purpose being to arrive at a true representation of ground resolution. For example, if a satellite is orbiting at 300 nautical miles and a 100 nautical mile ground swath is desired, then a straight line, m, joining scales a and e intersects scale c at 27 degrees, which is the required field of view for the lens.

If 70 mm film is selected for the format (picture size 2-1/4" by 2-1/4"), then the lens must have almost a 7-inch focal length, as indicated by line n and scale b. If the film has an effective resolution of, say, 100 line pairs/millimeter, then a line, p, through scales d and f will intersect scale g and indicate about 11, 5000 resolution elements. Finally, a line, q, between scales g and i intersects scale h at about 50, demonstrating this camera system will have a true ground resolution slightly in excess of 50 feet from an altitude of 300 nautical miles.

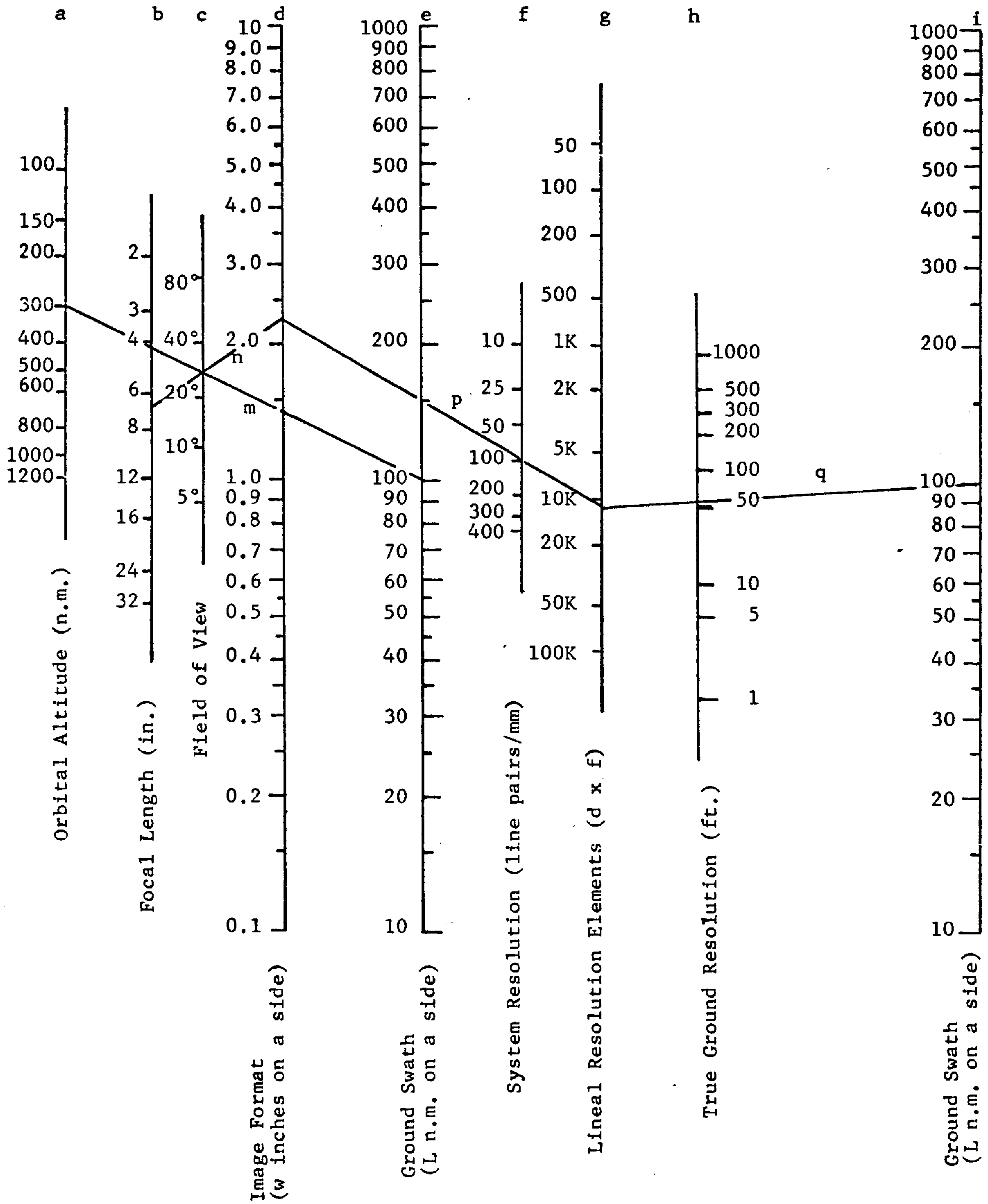


Figure A-4 IMAGER PARAMETER NOMOGRAPH

One important parameter which does not lend itself to nomograph representation is map scale. Although previously map scale has been shown to be a function of lens focal length and orbital altitude, Figure A-5 attempts to relate map scale and other parameters such as systems and ground resolution and generally to indicate the "performance" capability of the optics. Thus, for example, one can match systems resolution with focal length of the acquisition optics in the left section of Figure A-5 and by extending a horizontal line to the right from that intercept to the intercept with the appropriate altitude curve determine the potential ground resolution below. The map scale is shown in parenthesis for the representative focal lengths and is given for 100 nautical miles altitude. To determine map scale at higher altitudes, simply multiply the map scale by the appropriate factor - 2, 3, 4, and so forth - for altitudes of 200, 300, 400, and so forth, nautical miles, respectively. The dashed lines represent the 300 nautical mile curve, corresponding to a one-year orbital life and a 22-inch focal length, which is the required focal length to give 1:1,000,000 map scale at this altitude.

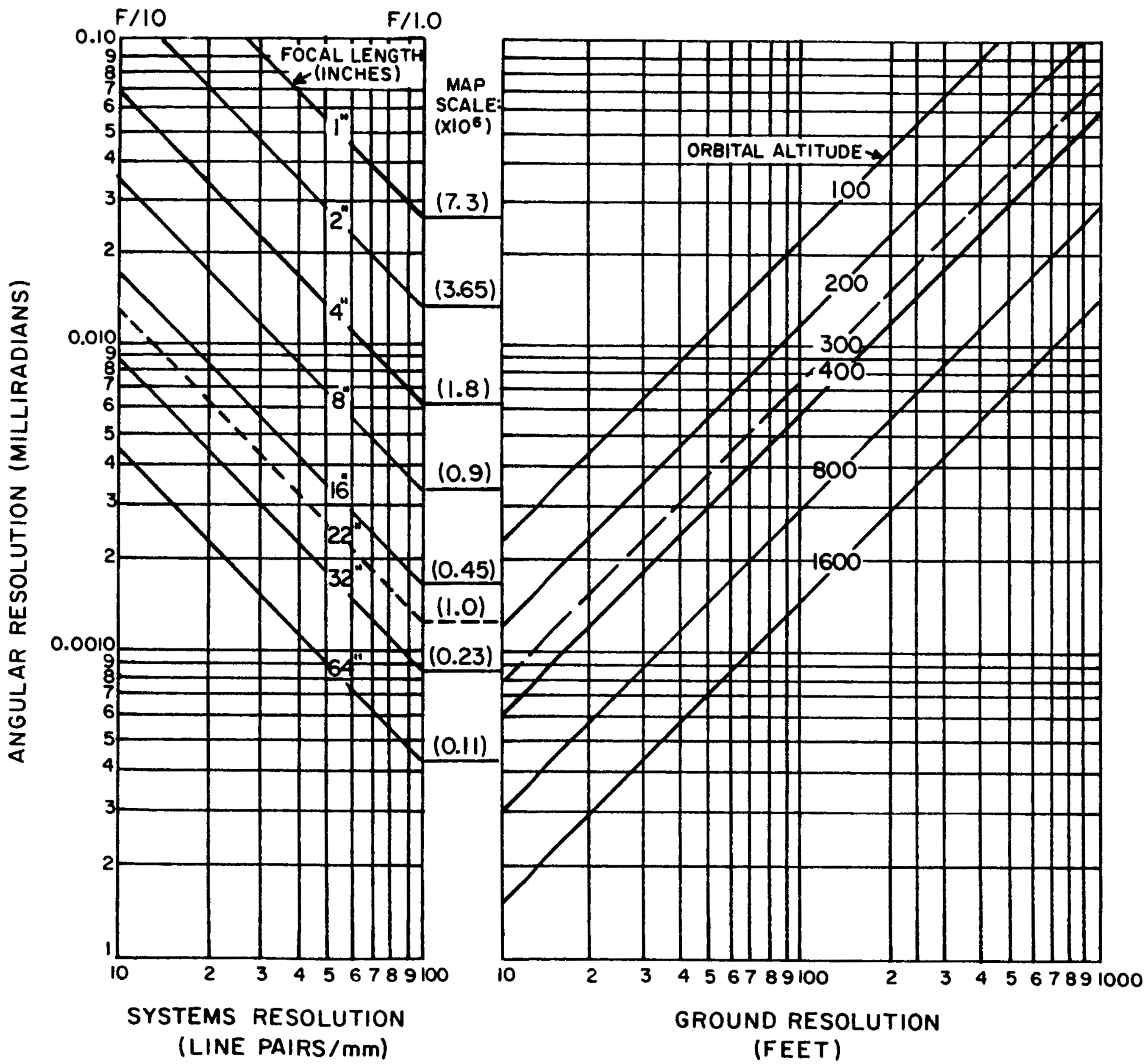


FIGURE A5. LENS PERFORMANCE CURVE